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COMPARISON OF SULPHUR

DIOXIDE DIFFUSION TRIALS

AT DUGWAY, UTAH AND O'NEILL, NEBRASKA

FRANK A. RECORD

PREPARED FOR

U. S. ARMY CMLC PROVING GROUND

DUGWAY, UTAH

NOVEMBER 1962

GEOPHYSICS CORPORATION OF AMERICA   BEDFORD, MASSACHUSETTS

COMPARISON OF SULFUR-DIOXIDE DIFFUSION
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SECTION I

INTRODUCTION

The purpose of this paper is to compare diffusion measurements
made at Dugway, using a continuous point source at ground level, with
values predicted by a regression analysis of similar data collected
during Project Prairie Grass over a Nebraska plain. During Project
Prairie Grass, a series of seventy diffusion experiments was carried
out under a variety of weather conditions with a dense network of sampl-
ing stations and with detailed supporting meteorological measurements.
A prediction technique based on the Prairie Grass data has been devel-
oped by Cramer[1-1] which uses the standard deviation of the azimuth
wind direction as predictor. Considerable evidence has accumulated to
support the use of similar techniques over different types of terrain,
and over surfaces with varying roughness characteristics.[1-2] [1-3] [1-4]
It is anticipated that the same method can be used successfully to esti-
mate gas concentrations at Dugway, and that the Prairie Grass results
may be used for the Dugway test area if suitable adjustments are made
to allow for site differences. A comparison of measurements made at
Round Hill with those of Prairie Grass[1-2] suggests that the differences
in site characteristics which are significant for diffusion may be de-
tected by comparing values of the standard deviation of the azimuth wind

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direction which have been measured under neutral stability conditions. This paper evaluates the usefulness of the Prairie Grass analysis for the Dugway test site by comparing a regression analysis of a series of Dugway trials with the more general and extensive Prairie Grass results.

SECTION II

SUMMARY OF EXPERIMENTAL TECHNIQUES

A detailed description of the field site, the experimental pro-
cedures followed during Project Prairie Grass, and a summary of the dif-
fusion and meteorological data collected has been presented elsewhere.[2-1]
Briefly, sulfur-dioxide gas was released horizontally into the atmosphere
at a uniform rate and at a height of 40 cm above ground level for a period
of 10 min. The rate of emission was varied from trial to trial according
to the anticipated rate of diffusion and ranged from about 40 to 100 g sec^{-1}.
The sampling network comprised midget impingers mounted at a height of
1.5 m along five concentric semicircular arcs located at travel distances
of 50, 100, 200, 400 and 800 m. An angular separation of 2 deg was used
along the four inner arcs, while a 1-deg separation was used at 800 m.
Nine impingers were also mounted on each of six lightweight towers at
the 100-m arc at heights from 0.5 to 17.5 m. During an experiment, the
sampling network was put in operation immediately prior to the start of
the gas release and continued in operation for several minutes after the
end of the release, until the tracer had cleared the 800-m arc. Gas
concentrations were determined by measuring the change in electrical con-
ductance of a hydrogen-peroxide solution contained in the impingers and
aspirated at a rate of either 1 or 1.5 l min^{-1} during the experiment.

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Meteorological instrumentation included: cup anemometers and wind-direction vanes mounted at a height of 2 m both near the release point for the tracer and at a distance of 450 m downwind; five bivanes, outfitted with heated-thermocouple anemometers, mounted at a height of 2 m near the downwind boundary of the field site; and shielded thermocouples and cup anemometers mounted on masts to provide temperature and wind speed profiles up to a height of 16 m.

Diffusion data collected at Dugway with sulfur-dioxide gas as the tracer and using field procedure similar to those followed at Prairie Grass are contained in Stanford Quarterly Reports 111-11 and 111-12.[2-2] [2-3] These measurements are satisfactory for comparison with the Prairie Grass results under neutral stability conditions, and are useful in appraising the unstable case. Unfortunately, almost no data were taken under conditions of moderate or extreme thermal stability. In the Dugway FP-SO_2 comparative field trails, the sulfur-dioxide gas was released at a constant rate for a period of 5 min and discharged horizontally in the downwind direction at a height of 4 ft above the ground. The release point for the gas was at the center of concentric sampling arcs with radii of 48, 100, and 200 yd; the arc spacing between sampling stations was 7 1/2 deg, with downwind stations aligned on radii of the test array. Source strengths ranged from 13.2 to 48.9 g sec^{-1}. Standard CW impinger bubblers filled with 15 ml of absorbing solution and having a flow rate of approximately 1 l min^{-1} were mounted at each station with the sampling inlet located 18 to 20 in. above the ground. During an experiment,

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aspiration was begun 30 sec prior to the start of the gas release and continued over a 12 to 20 min period. Sulfur-dioxide assessment was made using the fuchsin-formaldehyde colorimetric method as adapted for meteorological field trials by the Analytical Division, CW Laboratories, Dugway. All measurements were made at the East Tower Grid, Dugway, an area consisting of flat open terrain.

The meteorological data comprise wind speed and direction at the 2-m level measured at five stations, and temperature and wind speed measured at two of these five positions at heights of 1/2, 1, 2, 4, and 8 m. Wind data were recorded continuously on chart recorders.

Diffusion measurements were made on eight different days during April 1956. On each of the eight days, three separate trials were made at intervals of about one hour. Of these 24 trials, about half were carried out under near neutral conditions, 9 under various degrees of instability, and only 2 or 3 in the presence of well-defined temperature inversions. Of the stable trials, one has been omitted from the detailed analysis which follows because of doubtful concentration measurements.

SECTION III

METHOD OF ANALYSIS

The procedure used by the M.I.T. group in classifying the Prairie
Grass data was as follows: Least-squares regression lines were deter-
mined for the logarithms of the standard deviation of the azimuth wind
direction, σ_A, and the peak concentration, X_p, at each of the five travel
distances; regression lines were determined similarly for the logarithms
of σ_A and the standard deviation of the lateral concentration, σ_y, at
each distance. Values of X_p and σ_y were then calculated from the re-
gression analysis for selected values of σ_A covering a wide range of
stability conditions. Estimates for the standard deviation of concen-
tration along the vertical coordinate, σ_z, for each selected σ_A, were
computed at each distance by substituting the appropriate values of X_p
and σ_y into the expression

$$X_p = \frac{Q}{\pi \, \bar{u} \, \sigma_y \, \sigma_z} \quad , \qquad (1)$$

where Q is the source strength and $\bar{u}$ is the mean wind speed. Finally,
three charts were prepared showing the diffusion parameters X_p, σ_y, and
σ_z as a function of distance for each σ_A. Before being analyzed by the
above techniques, the Prairie Grass data were separated into daytime and
nighttime observations; regression analyses were carried out independently

on each data group. It should be pointed out that close agreement was
found between σ_z values calculated from Equation (1), which assumes that
the effluent is normally distributed along the lateral and vertical axes,
and the values of σ_z actually measured at 100 m.

For the Dugway experiments, source strengths, mean wind speeds, and
dosages at the three distances are tabulated in Quarterly Report 111-11.
The peak dosages reported at each sampling arc were converted to mg m^{-3},
and adjusted to a source strength of 100 g sec^{-1} and a mean wind speed
of 5 m sec^{-1}, to facilitate comparison with the Prairie Grass analysis.
Values for σ_y at 48, 100, and 200 yd were estimated from the cross-wind
dosages profiles of SO_2 presented in Quarterly Report 111-12 by dividing
the width of the plume (defined as the width between 1/10 peak limits)
by 4.3.

Since values of σ_A are not presented in the Stanford reports, a
substitute parameter must be used to classify the Dugway diffusion data.
Other field experiments have shown quite conclusively that σ_A is correlated
very highly with σ_y at 50 m[3-1] and is only slightly greater in mag-
nitude. This suggests that σ_y at 48 yd, when expressed in degrees, may
be used to classify the Dugway observations in exactly the same way
that σ_A was used to classify the Prairie Grass data. The results of the
two analyses may then be compared directly, making allowance for the
slight difference between σ_A and σ_y at 48 yd. Before carrying out the
analysis, an indirect check of the correlation between σ_y at 48 yd and
σ_A at Dugway was made by plotting the σ_y values against the extreme

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range of the 1-min average wind direction listed for each trial.
Figure 1 shows that the agreement is marked, the linear correlation
coefficient being +0.97; thus the use of σ_y at 48 yd as a substitute
for σ_A is supported, and the following analysis is based on this
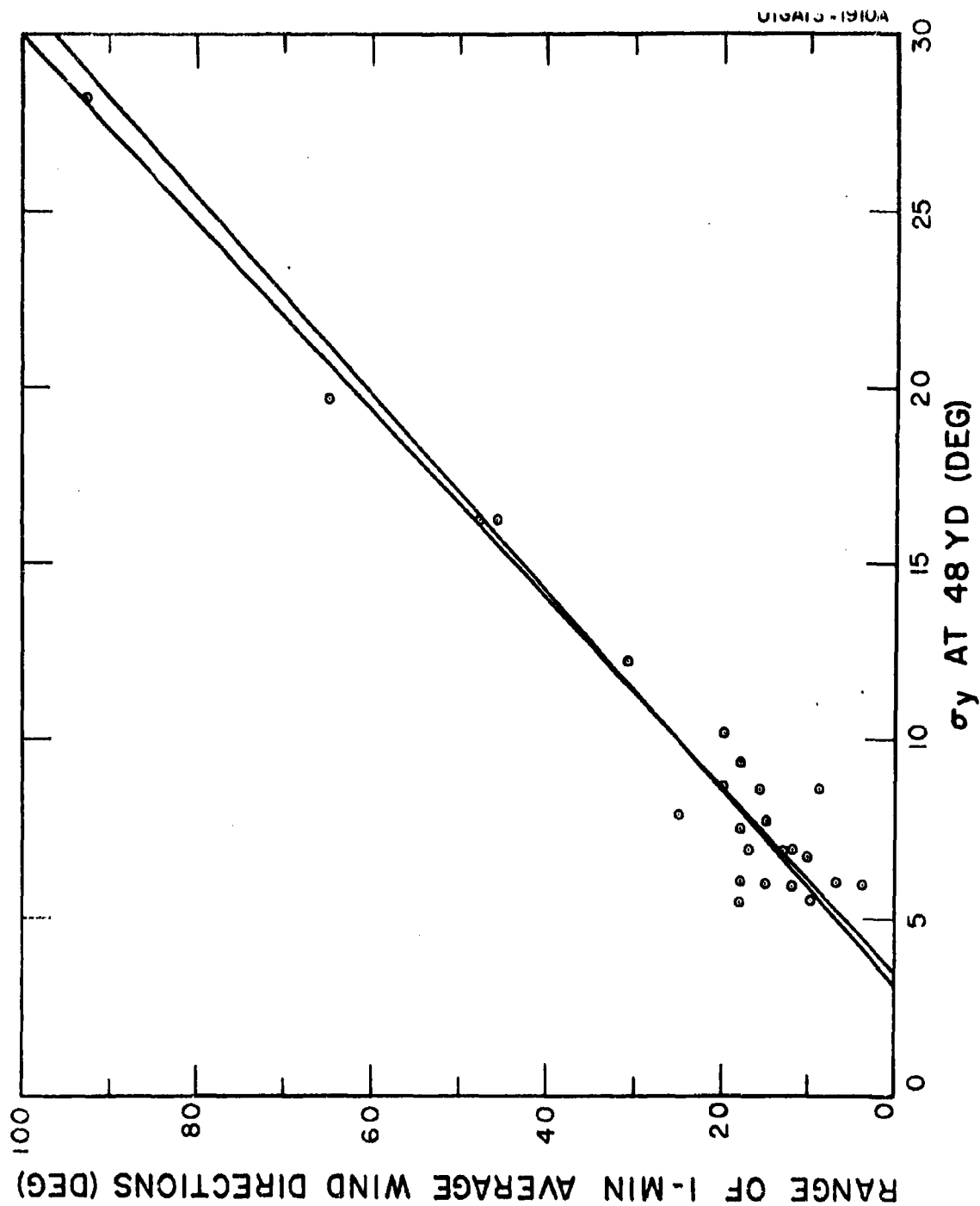relationship.

Figure 1. Range of 1-min average wind directions versus the crosswind standard deviation of concentration at 48 yd for the Dugway trials. Solid lines are least-squares regression lines.

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SECTION IV

REGRESSION ANALYSIS OF THE DUGWAY DATA

The Dugway data were separated into 14 daytime and 9 nighttime trials before the analysis was carried out, in spite of the lack of a satisfactory number of stable cases, so that comparison with the Prairie Grass analysis could be made on as similar a basis as possible. Figures 2 to 6 show the regression lines for X_p and σ_y at each distance as a function of σ_y at 48 yd, the parameter chosen to represent the missing σ_A. Values of σ_y at 48 yd were selected to cover the observed ranges (6 to 25 deg for the daytime observations, and 5 to 10 deg for the nighttime observations) and estimates of the two diffusion parameters X_p and σ_y obtained, at each travel distance, from the regression equations, and the appropriate points connected by straight lines. These summary estimates are presented in Figure 7 and Figure 8. Correlation coefficients and standard errors of estimates are listed in Table 1. Estimates of σ_z at each travel distance were computed from the relationship

$$\sigma_z = \frac{6366}{X_p \sigma_y} \quad ,$$

using the values of X_p and σ_y previously determined from the regression equations, and are shown in Figure 9.

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Table 1. Linear correlation coefficients $\underline{r}$ between σ_y at 48 yd and the two diffusion parameters X_p and σ_y at three travel distances. Standard errors of estimate, S_y, are expressed as factors by which estimates of variates should be multiplied to give limits within which approximately two-thirds of the cases are found. $\underline{N}$ is the sample size.

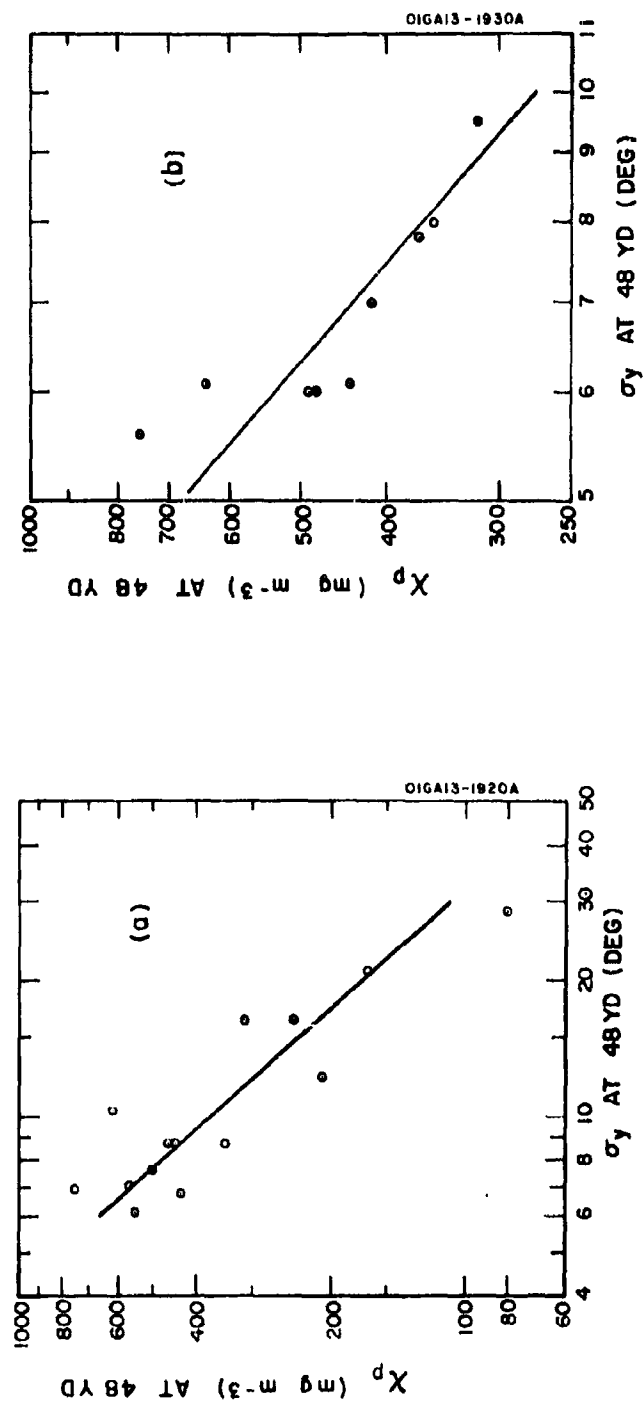| Travel distance	48 yd	100 yd	200 yd
	Daytime experiments $N = 14$		
$r(\sigma_y$ at 48 yd, $X_p)$	0.90	0.87	0.89
S_y	1.30	1.55	1.69
	0.77	0.64	0.59
$r(\sigma_y$ at 48 yd, $\sigma_y)$		0.99	0.95
S_y		1.08	1.16
		0.92	0.86
	Nighttime experiments $N = 9$		
$r(\sigma_y$ at 48 yd, $X_p)$	0.85	0.86	0.65
S_y	1.15	1.31	1.92
	0.87	0.77	0.52
$r(\sigma_y$ at 48 yd, $\sigma_y)$		0.90	0.70
S_y		1.10	1.22
		0.91	0.82

Figure 2. Peak concentration at 48 yd versus the crosswind standard deviation of concentration at 48 yd for (a) daytime and (b) nighttime Dugway trials. Concentrations are adjusted to a source strength of 100 g sec^{-1} and a mean wind speed of 5 m sec^{-1}. Solid lines are least-square regression lines.

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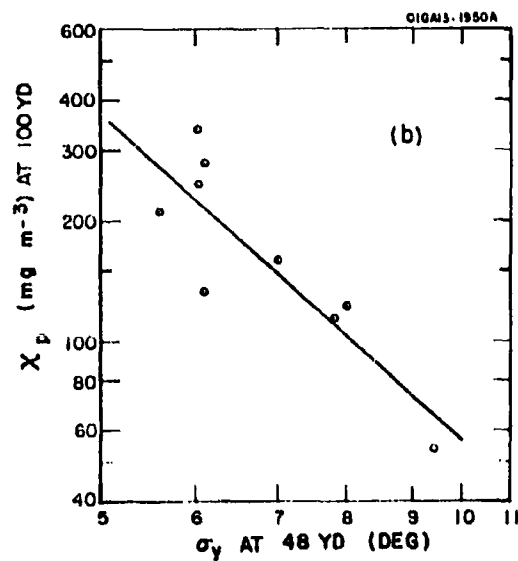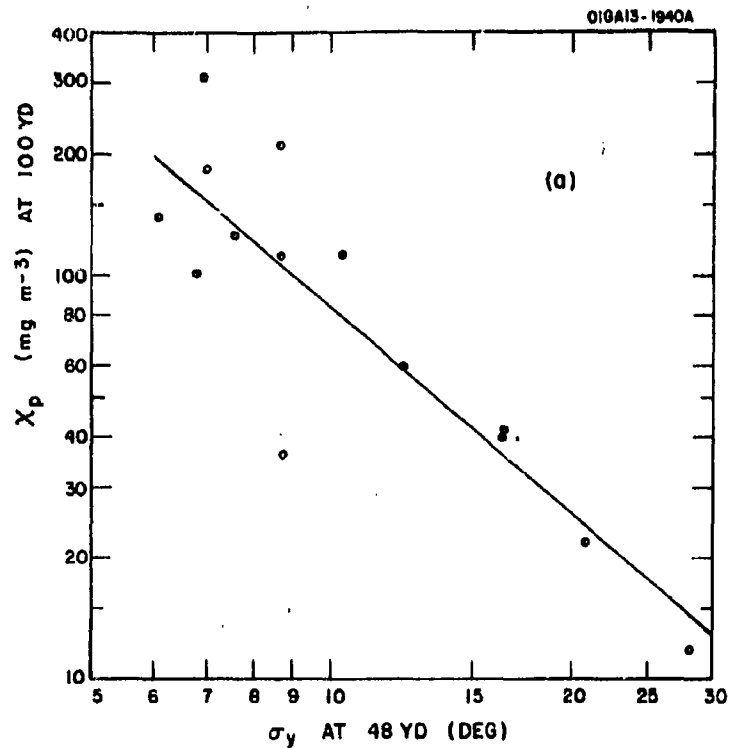
Figure 3. Peak concentration at 100 yd versus the crosswind standard deviation of concentration at 48 yd for (a) daytime and (b) nighttime Dugway trials. Concentrations are adjusted to a source strength of 100 g sec^{-1} and a mean wind speed of 5 m sec^{-1}. Solid lines are least-squares regression lines
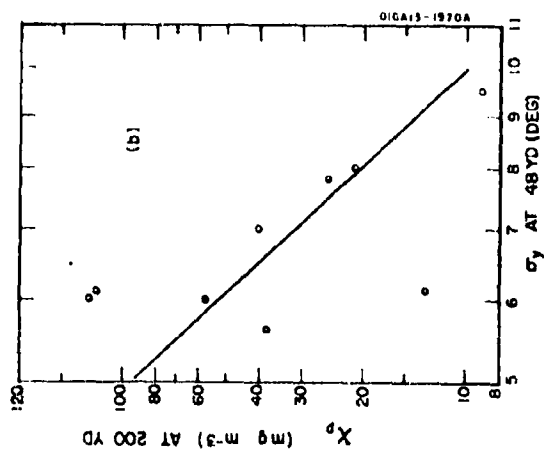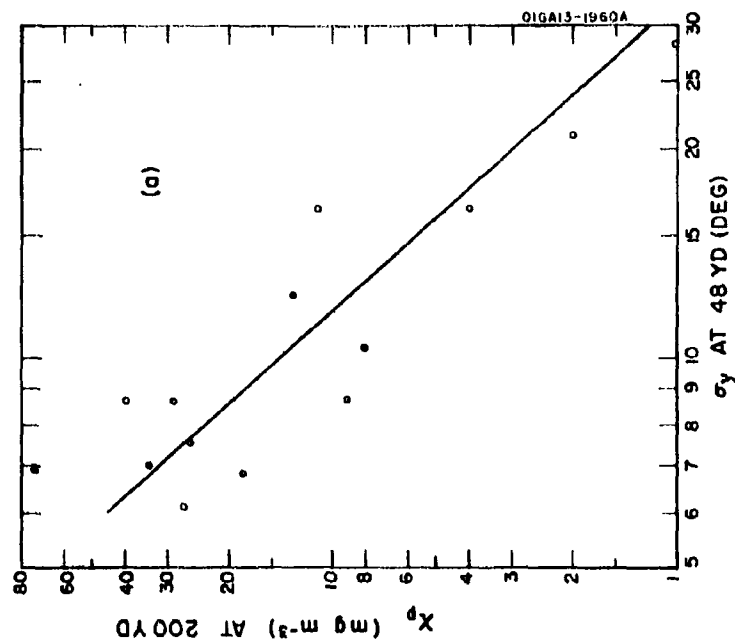
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Figure 4. Peak concentration at 200 yd versus the crosswind standard deviation of concentration at 48 yd for (a) daytime and (b) nighttime Dugway trials. Concentrations are adjusted to a source strength of 100 g sec^{-1} and a mean speed of 5 m sec^{-1}. Solid lines are least-squares regression lines.

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Figure 5. Crosswind standard deviation of concentration at 100 yd versus the same parameter at 48 yd for (a) daytime and (b) nighttime Dugway trials. Solid lines are least-squares regression lines.
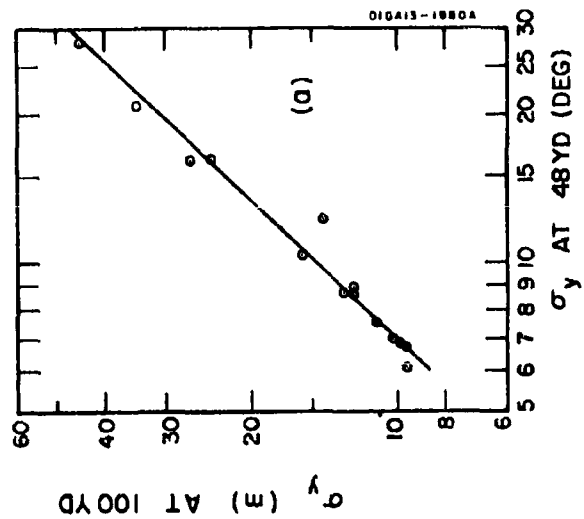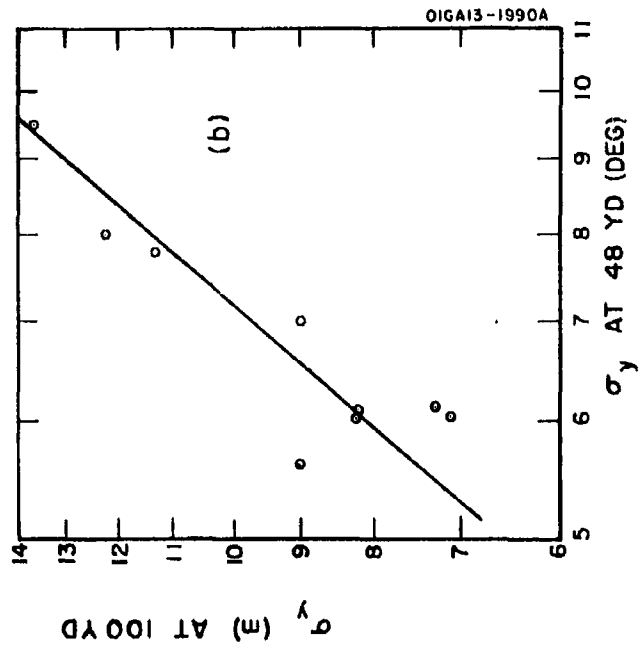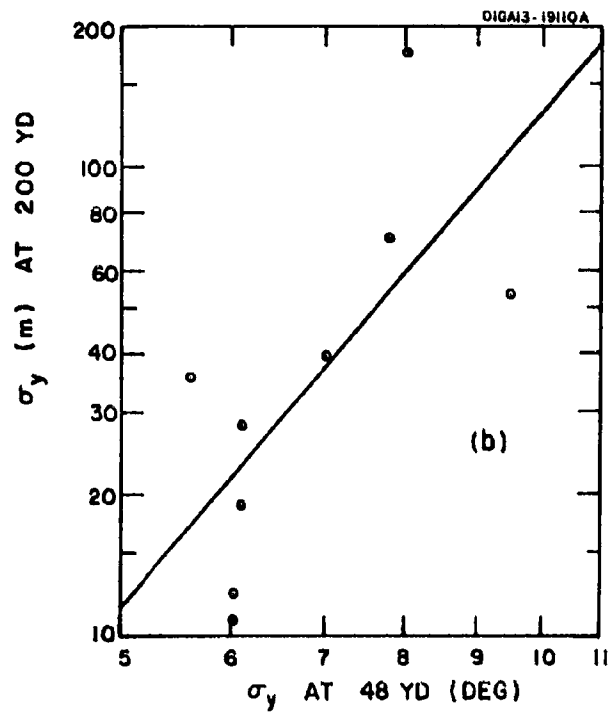
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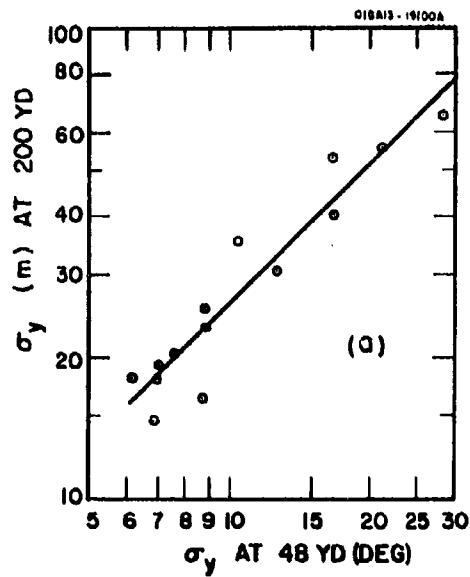
Figure 6. Crosswind standard deviation of concentration at 200 yd versus the same parameter at 48 yd for (a) daytime and (b) nighttime Dugway trials. Solid lines are least-squares regression lines.

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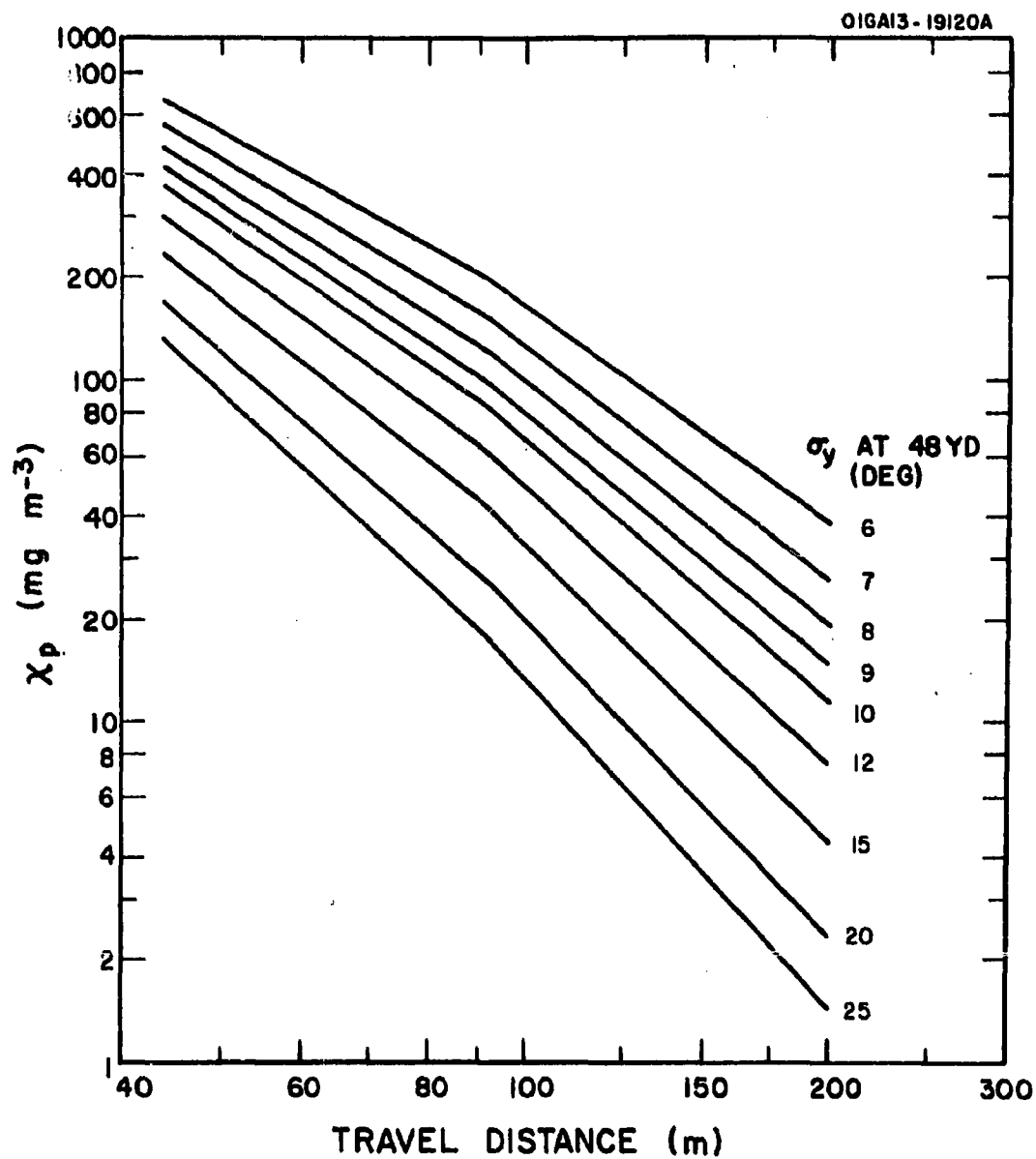
Figure 7a. Peak concentration for the Dugway daytime trials; values
are adjusted to a source strength of 100 g sec⁻¹ and a
mean wind speed of 5 m sec⁻¹.
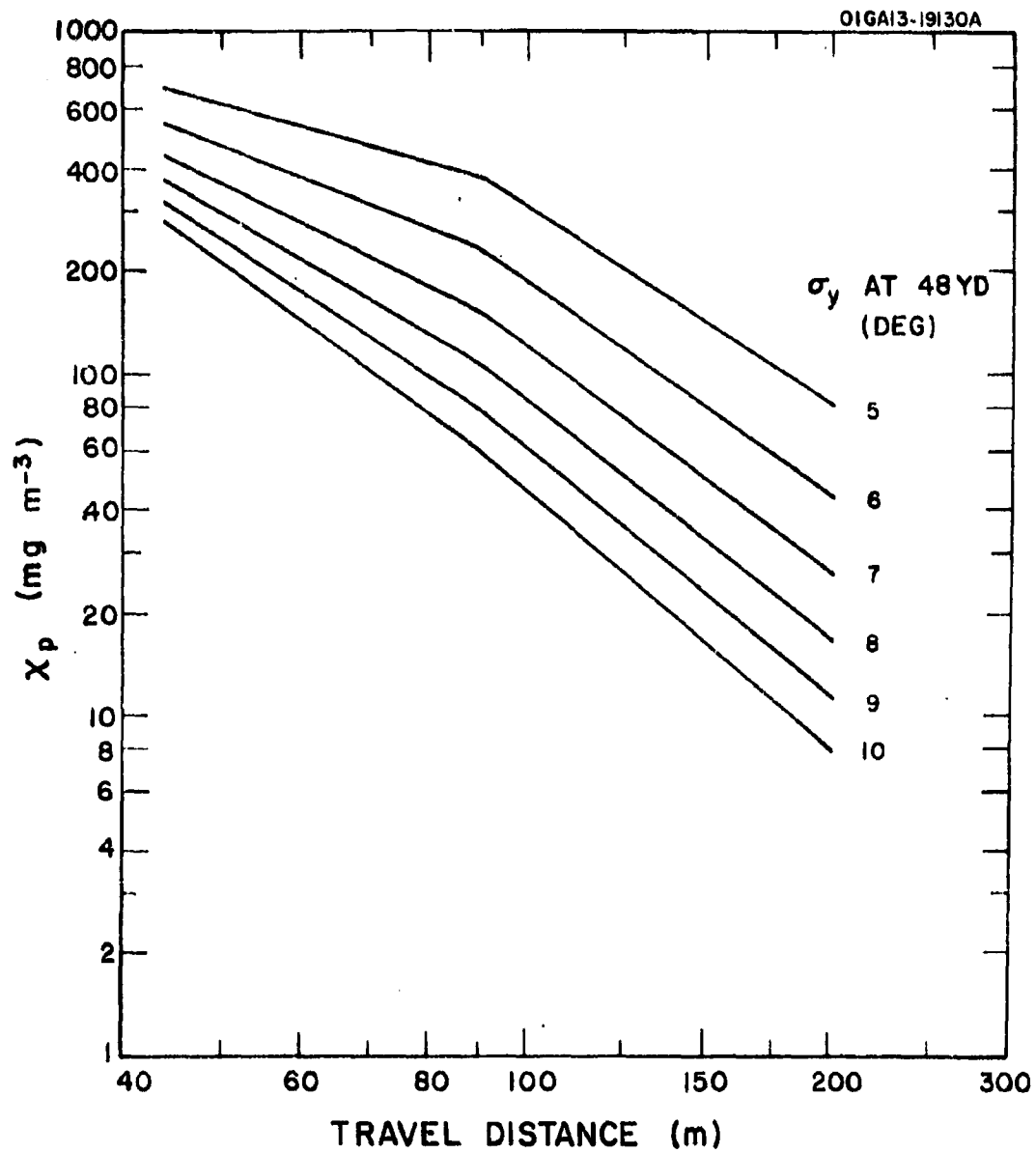
Figure 7b. Peak concentration for the Dugway nighttime trials; values are adjusted to a source strength of 100 g sec^{-1} and a mean wind speed of 5 m sec^{-1}.

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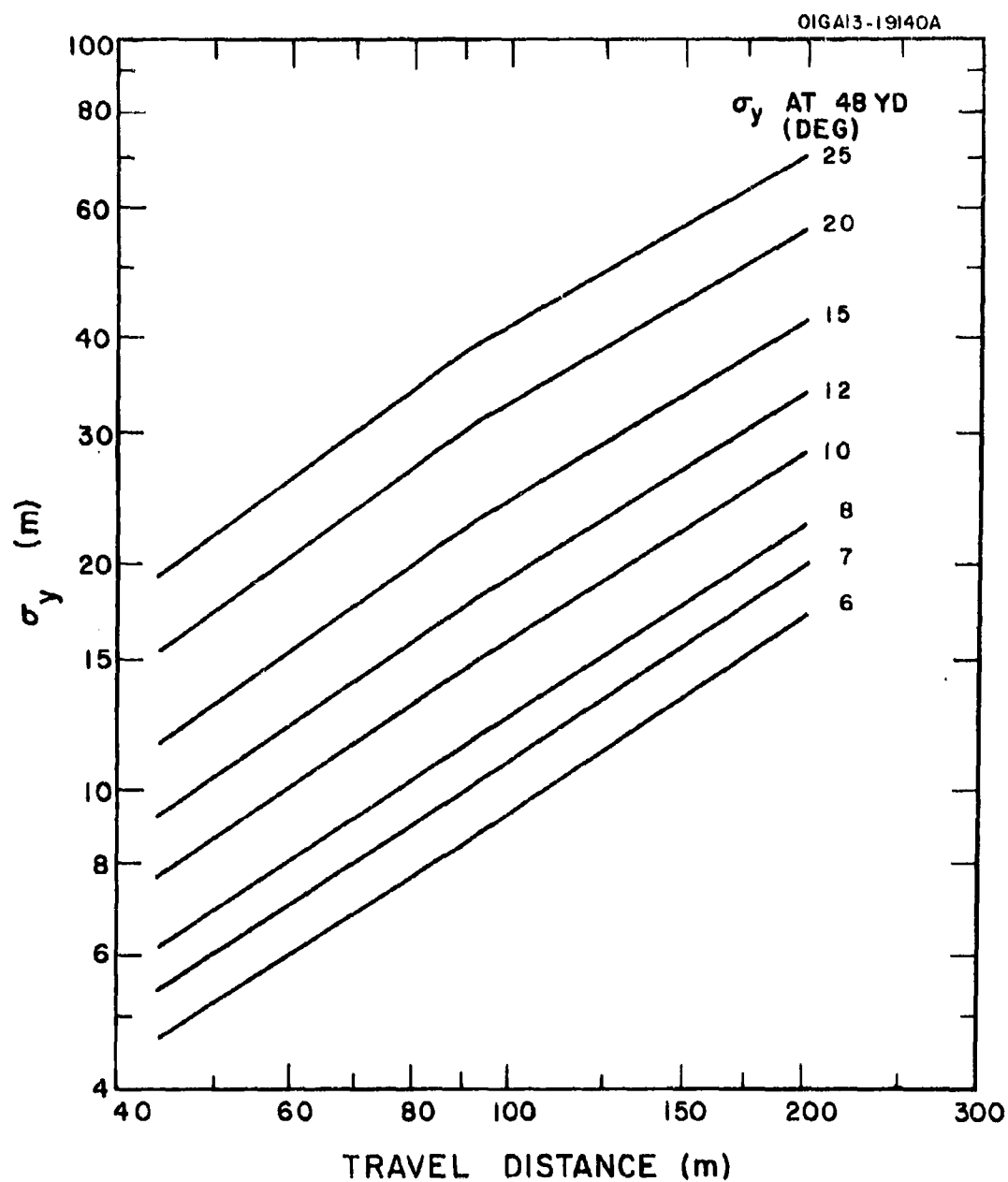
Figure 8a. Crosswind standard deviation of concentration for the Dugway daytime trials; values are expressed in terms of arc distance.

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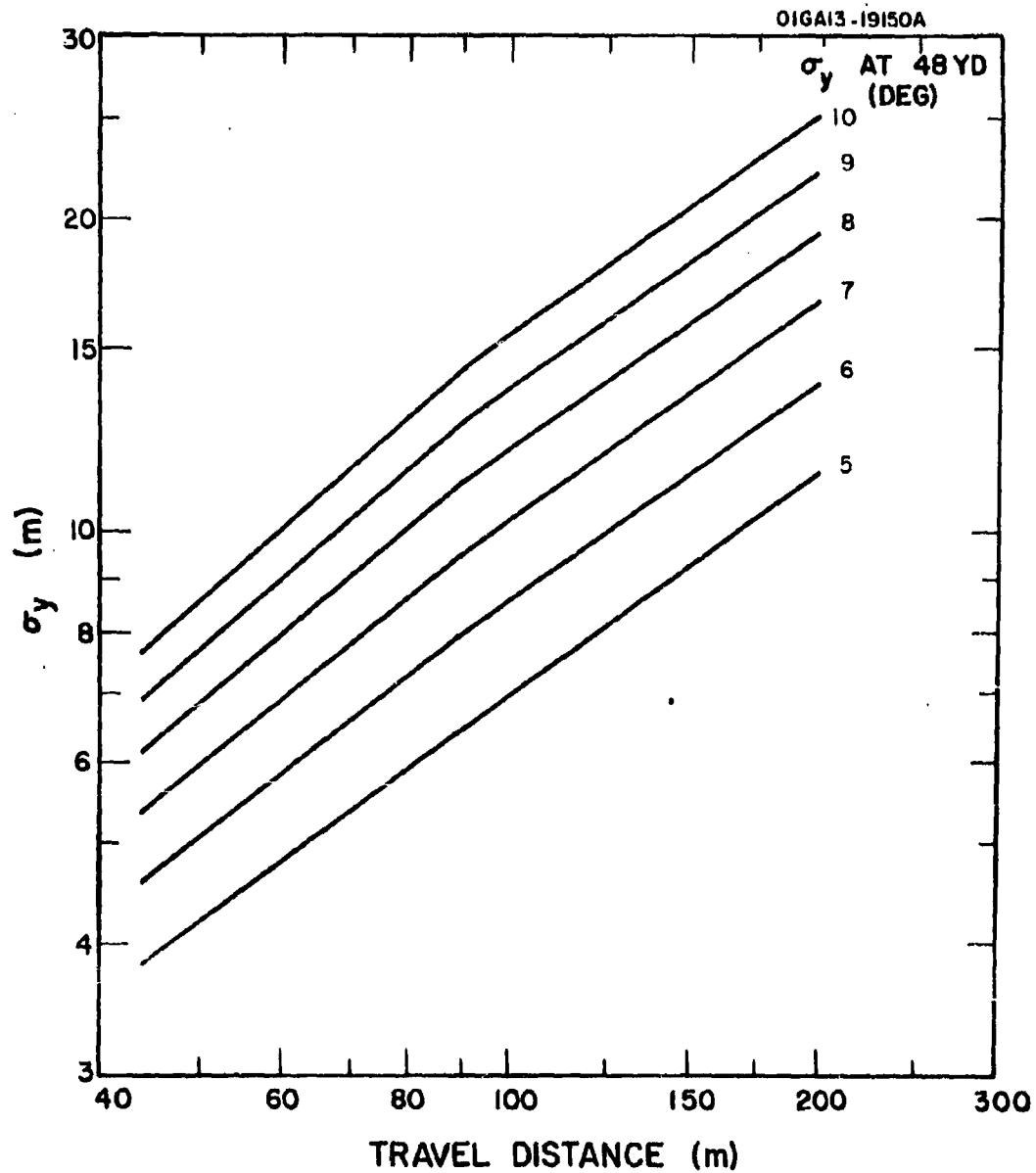
Figure 8b.   Crosswind standard deviation of concentration for the
Dugway nighttime trials; values are expressed in terms
of arc distance.

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Figure 9a. Estimates of standard deviation of concentration along the vertical for the Dugway daytime trials; values are expressed in terms of arc distance.

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Figure 9b. Estimates of standard deviation of concentration along the
vertical for the Dugway nighttime trials; values are expressed
in terms of arc distance.

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SECTION V

COMPARISON OF THE DUGWAY AND PRAIRIE GRASS RESULTS

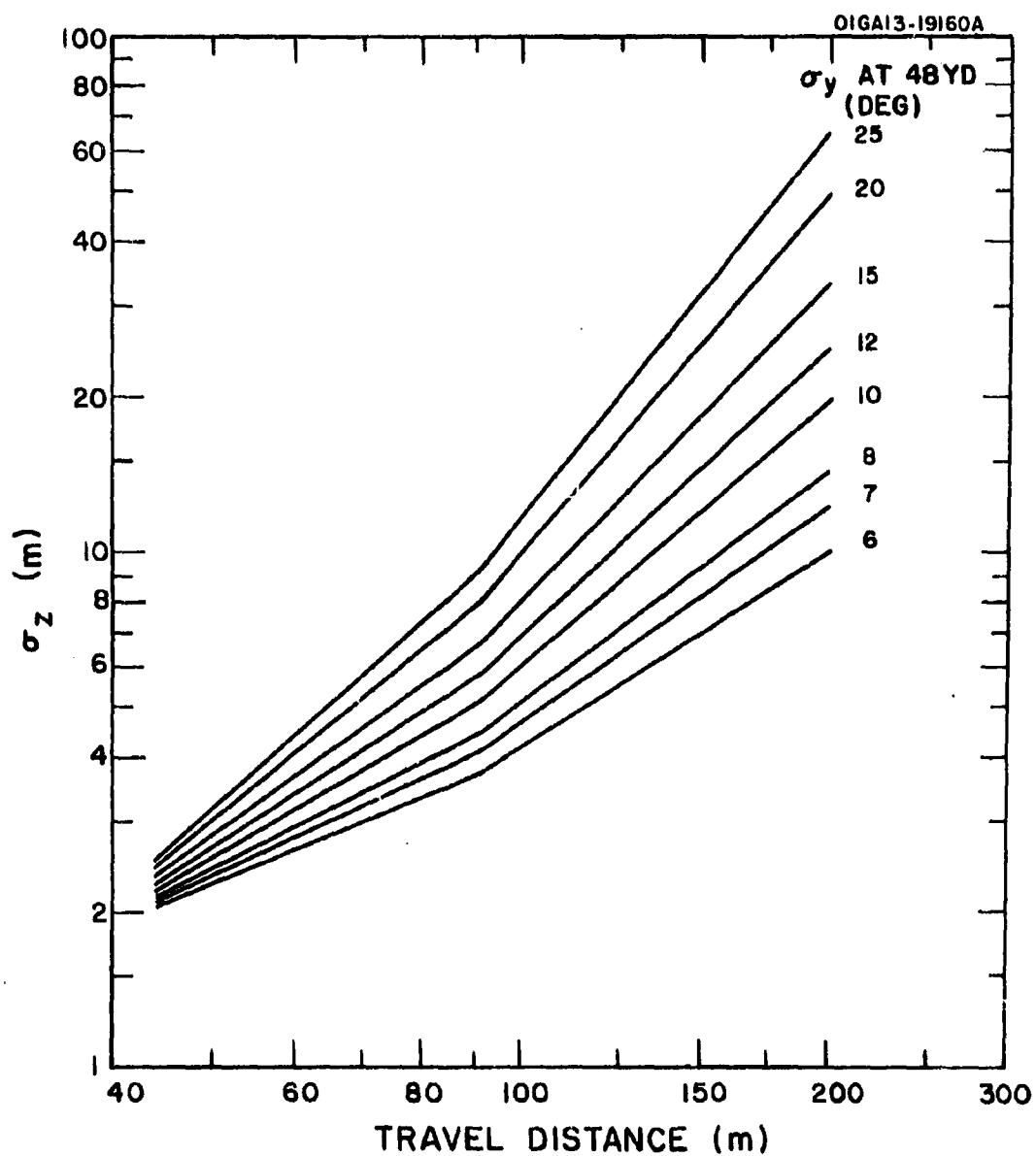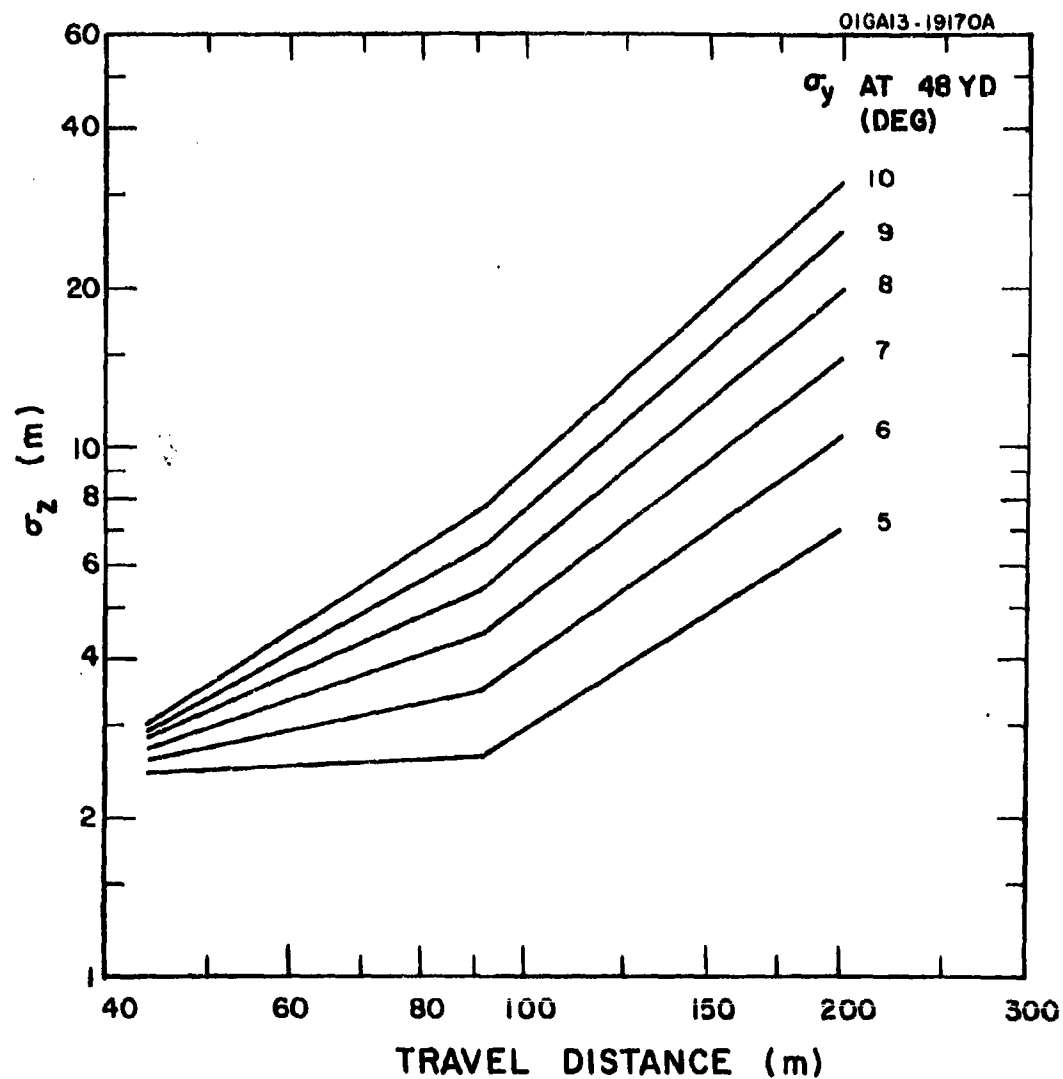Two minor adjustments should be made in the results of the Dugway
regression analysis before they are compared with the values of the
diffusion parameters predicted by the Prairie Grass analysis. As
mentioned previously, a value of σ_y at 48 yd is the equivalent of a
somewhat larger value of σ_A, the exact relationship used in this com-
parison being based on a regression analysis of σ_A and σ_y at 50 m for
the Prairie Grass experiments. Figure 10 shows the regression line
between these variables for the 22 daytime and 22 nighttime experiments
used in classifying the Prairie Grass observations. From the analysis,
$\sigma_A = 1.54 + 0.93 \sigma_y$, and the linear correlation coefficient is +0.95.
The second adjustments make allowance for the difference between 5-
and 10-min means of σ_y and χ_p. Stewart, Gale and Crooks[4-1] have re-
ported that the general relationship between concentration and the
duration of the sampling interval follows a one-fifth power law. Data
obtained by the Massachusetts Institute of Technology[4-2] indicate that
the same power law applies for sampling intervals from 10 min to 3 sec.
To convert 5-min values to 10-min estimates it is assumed that $R \propto t^{-0.2}$,

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Figure 10. Standard deviation of azimuth wind direction versus the crosswind standard deviation of concentration at 50 m for Prairie Grass data. Daytime experiments are indicated by open circles and nighttime experiments by filled circles.

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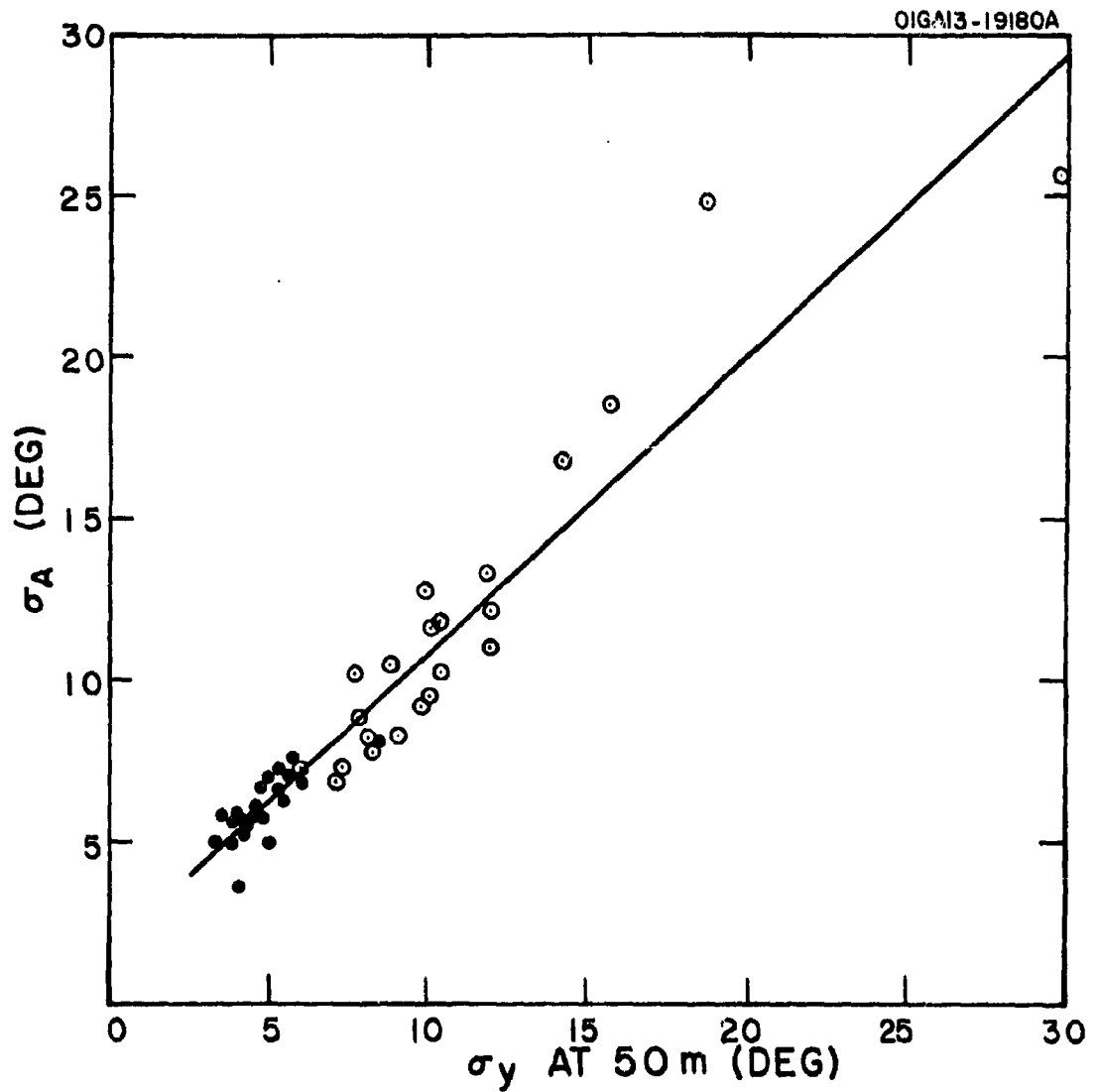
where

$$R = \frac{X_p(t \text{ min})}{X_p(10 \text{ min})} = \frac{\sigma_y(10 \text{ min})}{\sigma_y(t \text{ min})} \quad ;$$

thus

$$\frac{X_p(5 \text{ min})}{X_p(10 \text{ min})} = \frac{\sigma_y(10 \text{ min})}{\sigma_y(5 \text{ min})} \approx 1.15 \quad .$$

Table 2 shows equivalent values of σ_A and σ_y at 48 yd under the preceding assumptions.

Since the lower limit of σ_y at 48 yd observed over the 5-min sampling period at Dugway was about 6 deg, the comparison with the Prairie Grass analysis has been limited to $\sigma_A \geq 8$ deg. To obtain estimates for comparison, the Dugway summary charts (Figures 7 and 8) were entered at the three distances of 50, 100, and 200 m and values of X_p and σ_y interpolated for σ_y at 48 yd equal to 6.0, 7.9, 12.6 and 21.9 deg. Averages of both daytime and nighttime estimates were used at 6.0 and 7.9 deg to represent neutral conditions; no attempt was made to obtain estimates for stable nighttime conditions, because of data limitations. Since these estimates represent 5-min values, peak concentrations were divided by 1.15 and standard deviations of plume width were multiplied by 1.15 to obtain the 10-min values shown in Table 3. These final estimates were also used to compute estimates of σ_z. Table 3 presents the comparison between values of the three diffusion parameters predicted

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Table 2. Relationship between selected σ_A values (deg) computed over a 10-min period and equivalent values of σ_y (deg) at 48 yd for 10 - and 5-min periods.

σ_A (10 min)	σ_y at 48 yd (10 min)	σ_y at 48 yd (5 min)
5	3.7	3.2
6	4.8	4.2
8	6.9	6.0
10	9.1	7.9
15	14.5	12.6
25	25.2	21.9

Table 3. Comparison between Dugway and Prairie Grass diffusion para-. meters at three travel distances. Concentrations are adjusted to a standard source strength of 100 g sec^{-1} and a mean wind speed of 5 m sec^{-1}. Values are based on regression analyses and represent 10-min estimates. Tabulated values are adjusted Dugway parameters; values predicted by the Prairie Grass analysis are in parenthesis.

Travel distance	50 m	100 m	200 m
σ_A (10-min)		χ_p (mg m^{-3})	
8	435 (394)	148 (132)	35 (39)
10	296 (272)	80 (78)	16 (20)
15	189 (185)	36 (43)	6.1 (9.6)
25	95 (114)	14 (21)	1.7 (3.7)
		σ_y (m)	
8	5.9 (5.8)	10.4 (10.8)	17.7 (19.8)
10	7.7 (8.4)	14.0 (15.1)	24.2 (27.5)
15	12.4 (12.7)	23.0 (23.0)	41.2 (43.0)
25	21.5 (20.8)	41.2 (38.5)	70.5 (75.0)
		σ_z (m)	
8	2.5 (2.8)	4.1 (4.5)	10.3 (8.2)
10	2.8 (2.8)	5.7 (5.4)	16.8 (11.6)
15	2.7 (2.7)	7.6 (6.4)	25.3 (15.4)
25	3.1 (2.7)	11.1 (7.9)	53.1 (22.9)

by the Prairie Grass regression analysis and the Dugway results, adjusted as explained above. Prairie Grass estimates for σ_A = 8 deg are averages of predictions based on both the daytime and nighttime analyses.

Inspection of Table 3 shows very close agreement between the results at the two sites under neutral conditions (σ_A = 8 deg), the observed differences probably being within the limits of experimental error. Somewhat larger differences in X_p and σ_z are observed with increasing instability and with increasing distance from the source, reaching a maximum of about a factor of two for σ_A = 25 deg and a travel distance of 200 m. This suggests the possibility that for a given σ_A under conditions of moderate instability, greater vertical exchange takes place over the more arid Dugway test site than over the Nebraska prairie. More extensive data taken at Dugway during conditions of instability would be required to determine whether these differences are indeed a consequence of differences in site characteristics, or simply result from the small sample size available for analysis or from the experimental procedure followed.

Figure 11 is a plot of σ_y at 48 yd versus the stability ratio, defined as the temperature difference in degrees Celsius between 4m and 0.5 m divided by the square of the wind speed at 2 m. At SR = 0, average value given by the regression lines is 6.4 deg. When this value is adjusted for both sampling time and for the difference between σ_A and σ_y at 48 yd, the value for σ_A (10 min) at Dugway for neutral conditions becomes 8.4 deg. This compares very favorably with the value of about 7 deg determined from the Prairie Grass data, and implies similar site characteristics at two locations.

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Figure 11. Crosswind standard deviation of concentration at 48 yd versus the Stability Ratio for the Dugway trials. Solid lines are least-squares regression lines; the two points beyond the limits of the regression lines were omitted in the analysis.

SECTION VI

CONCLUSIONS

Under neutral stability conditions, no significant differences
were found between the Dugway and Prairie Grass diffusion patterns over
the 200 m travel distance, and the direct use of the Prairie Grass re-
gression analysis as a tool for predicting diffusion at Dugway over
distances approaching 1 km appears to be justified. Because of the
limited amount of Dugway data collected under conditions of moderate
instability, the comparison over the thermally unstable range is tenta-
tive. The analysis does suggest that the Prairie Grass results may
underestimate the amount of diffusion taking place under strong thermal
instability, and that significant differences may occur over travel
distances greater than 200 m. No comparison was possible for moderate to
extreme thermal stratification, because of the lack of Dugway data; it is
expected, however, that differences under such conditions would be small.

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